# ARTICLE COMPRISING A MEMS DEVICE AND METHOD THEREFOR

## Field of the Invention

The present invention relates generally to micro-electromechanical systems ("MEMS") devices. More particularly, the present invention relates to a MEMS device that is movable between a first position located within a multi-layer substrate and a second position that is located outside of the substrate.

## Background of the Invention

MEMS technology is becoming ubiquitous. MEMS accelerometers, pressure sensors, and even MEMS-based electrical components have been developed for use in a wide variety of applications.

Presently, some of the most important applications for MEMS are in the area of optical communications, wherein MEMS-based optical modulators, switches, attenuators, filters and like devices have been developed. While MEMS technology is very well suited for optical communications applications, integrating MEMS devices into such systems does present certain challenges. In particular, to process an optical signal via a MEMS device, the MEMS device must typically capture or engage the optical signal in a region of space that is "out-of-the-plane" relative to the substrate layer of the MEMS device. In other words, a raised or three-dimensional MEMS component is required to capture the signal.

Such components have traditionally been fabricated as "flip-up" structures that incorporate micro-hinges. Flip-up structures are formed by (1) fabricating hinged plates that lie on a base or substrate layer; (2) raising the hinged plates by rotating them about their micro-hinges; and (3) locking the hinged plates into the raised position. *See, e.g.*, U.S. Pat. Nos. 5,923,798 and 5,963,367; Pister et al., "Microfabricated Hinges," Sensors and Actuators A, vol. 33, pp 249-256 (June 1992); Lee et al., "Surface-Micromachined Free-Space Fiber Optic Switches with Integrated Microactuators for Optical Fiber Communication Sytsems," Transducers '97, 1997 Int'l. Conf. Solid-State Sensors and Actuators, Chicago, June 16-19, 1997, pp 85-88, and Reid et al., "Automated Assembly of Flip-Up Micromirrors," Transducers '97, 1997 Int'l. Conf. Solid-State Sensors and Actuators, Chicago, June 16-19, 1997, pp 347-350.

While flip-up optical MEMS structures represent a tremendous advance over earlier bulk devices having moving parts, they nevertheless suffer from certain drawbacks.

For instance, many of the MEMS foundries offer fabrication processes that use alternating layers of oxide and polysilicon to form the various plates and other elements of a MEMS structure. Typically, the polysilicon layers exhibit compressive stress that can cause the fabricated elements to warp. Warped elements can cause assembly and operational problems. Additionally, flip-up structures must be assembled. In some cases, processing steps and structures are required for no reason other than to drive the assembly process.

Furthermore, optical applications often have stringent placement tolerances (*e.g.*, for single mode fiber, *etc.*). Due to the nature of (*i.e.*, the "play" in) micro-hinges, rotating a plate or other hinged element into a precise position is problematic. Moreover, once a hinged element is moved to a desired position, it must be locked in place. The locking mechanism is often realized as an additional notched plate that is rotated into interlocking engagement with the hinged element. Again, the notched plate represents additional fabrication and assembly steps.

The art would therefore benefit from an article that offers the functionality of the flip-up structures of the prior art but avoids at least some of their drawbacks.

## Summary of the Invention

The present invention is directed to a MEMS device that avoids some of the drawbacks of the prior art. The present MEMS device, which is fabricated from a multi-layer substrate, comprises a support portion coupled to an element portion. In some embodiments, the MEMS device is configured as an optical switching element, wherein, for example, the element portion is physically adapted to receive and reflect an optical signal. It is to be understood, however, that such embodiments are merely illustrative; in other embodiments, the present MEMS device is suitably used as other than an optical switching element.

The multi-layer substrate that forms the present MEMS device has at least a first layer, a second layer and an intermediate layer that separates the first and second layers. In accordance with the present teachings, the element portion of the MEMS device is fabricated from the second layer of the multi-layer substrate. Furthermore, it is particularly advantageous if the element portion has a major surface that is defined by the thickness of the second layer of the multi-layer substrate. When formed this fashion, the element portion itself is substantially orthogonal to the major surface of the surrounding multi-layer substrate.

In one embodiment, the multi-layer substrate is a silicon-on-insulator wafer. The support portion is advantageously formed from the top, relatively thin silicon layer of the silicon-on-

insulator wafer, while the element portion is formed from the bottom, relatively thick silicon layer of the wafer.

In some embodiments, the support portion of the MEMS device includes an actuating plate, one or more torsional members and a beam. The beam advantageously rigidly couples the actuating plate to the element portion. The torsional members, which depend from the beam, are coupled to the first layer of the multi-layer substrate (from which the torsional members are formed). The MEMS device is therefore supported, via the torsional members, from the multi-layer substrate. The torsional members are operative to twist, thereby allowing the MEMS device to move (*e.g.*, rotate, *etc.*) independently of the multi-layer substrate.

The actuating plate and the element portion, which depend from the beam, are disposed on opposite sides of an axis of rotation that is aligned with the torsional members (*i.e.*, the axis of rotation of the beam). Furthermore, the actuating plate is advantageously rigidly coupled to the element portion. This configuration functions as a mechanism by which at least some of the element portion formed from the second layer is raised "above" the first layer of the substrate.

Specifically, in a first position, the element portion is disposed *within* the multi-layer substrate. In some embodiments, the first position results when the MEMS device is in an unactuated state (*i.e.*, no potential difference between the actuating plate and the underlying electrode). In an actuated state, a potential difference is created across the actuating plate and the electrode, thereby generating an electrostatic force of attraction therebetween. When the electrostatic force exceeds the restoring force of the torsional members, the actuating plate moves toward the underlying electrode such that the beam rotates about its axis of rotation. As the actuating plate moves downwardly toward the electrode, the element portion moves upwardly *out* of the multi-layer substrate to a second position in seesaw-like fashion. When the actuating force is removed, the element portion drops back within the multi-layer substrate to the first position.

The term "**restoring force**," as used herein, is the force of the torsional elements that must be overcome in order to move the element portion from its unactuated state to its actuated state. The term "**unactuated state,**" or "**first position**" as used herein, refers to when the element portion is within (*i.e.*, beneath the surface of) the multi-layer substrate. The term "**actuated state**," or "**second position**," as used herein, refers to when the element portion is outside (*i.e.*, above the surface) of the multi-layer substrate.

In the context of an optical switching element, the element portion is used to direct an optical signal. For example, in one embodiment, the two optical fibers are positioned end-to-end,

with a gap between the ends, over the multi-layer substrate. The element portion of the present MEMS device is aligned with the gap between the fiber ends. When the MEMS device is in the first position within the multi-layer substrate, the optical signal is able to pass from the first fiber to the second fiber. When, however, the MEMS device is actuated, the optical signal does not pass from the first fiber to the second fiber since the element portion is raised above the surface of the multi-layer substrate and into the path of the optical signal.

In such embodiments, the element portion is configured and placed to direct the optical signal either back to the input source of the optical signal (*i.e.*, the input fiber or input waveguide) or to a different fiber or waveguide. Thus, the optical switching element is used to either redirect or reflect the optical signal.

## Brief Description of the Drawings

**FIG. 1** depicts an *n* x *n* array of MEMS devices in accordance with the illustrative embodiment of the invention.

**FIG. 2** depicts a top view of an illustrative embodiment of one of the MEMS devices of FIG. 1.

**FIG. 3** depicts a side cross-sectional view of the MEMS device of FIG. 2, wherein the MEMS device is in an unactuated state.

**FIG. 4** depicts the side cross-sectional view of FIG. 3, but when the MEMS device in an actuated state.

**FIG. 5** depicts a flow diagram of a method for making a MEMS device in accordance with the present teachings.

**FIG. 6** depicts a method for carrying out one of the operations in the method depicted in FIG. 5.

**FIG. 7** depicts the processing of the top side of a SOI wafer during the fabrication of a MEMS device in accordance with the present teachings.

**FIG. 8** depicts the processing of the bottom side of a SOI wafer during the fabrication of a MEMS device in accordance with the present teachings.

**FIG. 9** depicts dimensional parameters of a MEMS device for use in conjunction with a physical design example.

**FIG. 10** depicts a plot of reduced actuation voltage versus reduced rotation angle.

**FIG. 11** depicts a top view of an improved chopper switch in accordance with the present teachings.

**FIG. 12** depicts a cross-sectional side view of the chopper switch of FIG. 11 through line **1-1** of FIG. 11.

**FIG. 13** depicts an optical cross connect comprising a *n* x *n* array of MEMS devices in accordance with the present teachings.

## Detailed Description of the Invention

### *Structure and Operation of thePresent MEMS Device*

FIG. 1 depicts a *n* x *n* array of MEMS devices **100** in accordance with the illustrative embodiment of the present invention. For the illustrative array depicted in FIG. 1, *n* equals 3. That is, there are three columns and three rows of MEMS devices **100**. It will be understood that in other embodiments of the *n* x *n* array, *n* is less than 3, and in still further embodiments, *n* is greater than 3. As described later in this *Specification*, the illustrative *n* x *n* array of MEMS devices can function as an optical cross connect, among other uses.

A first embodiment of a MEMS device **100** is depicted in FIGS. 2-4. FIG. 2 depicts a top view of MEMS device **100**, while FIGS. 3 and 4 depict cross-sectional side views.

With reference to FIGS. 1-4, each MEMS device **100** comprises a support portion **102** and element portion **110** (FIG. 1) that are substantially separated from multi-layer substrate **112** by trench **222** (FIG. 2).

In the illustrative embodiment, support portion **102** comprises torsional members **104**, beam **106** and actuating plate **108**. Torsional members **104** rotatably couple MEMS device **100** to multi-layer substrate **112**. Torsional members **104** depend from beam **106** at a location between actuating plate **108** and element portion **110**. Torsional members **104** create a "pivot point" along beam **106** between actuating plate **108** and element portion **110** about which beam **106** rotates in the manner of a "see-saw" when suitably actuated.

In some embodiments, multi-layer substrate **112** comprises three layers, including a bottom, relatively thick layer **114** (also referred to herein as the "**second layer**"), an intermediate, relatively thin layer **116** disposed on bottom layer **114**, and a top, relatively thin layer **118** (also

referred to herein as the "**first layer**") disposed on intermediate layer **116**. As described in more detail later in this *Specification*, MEMS device **100** is advantageously formed from some of the layers comprising multi-layer substrate **112**.

MEMS devices **100** are movable between two states or positions that are depicted in FIG. 1. In particular, in a first position illustrated by MEMS device **100-1**, a MEMS device resides substantially within multi-layer substrate **112**. More particularly, the upper surface of MEMS devices **100** (*i.e.*, the upper surfaces of torsional members **104**, actuating plate **108** and beam **106**) is co-planar with upper surface **120** of multi-layer substrate **112**, while element portion **110** resides *within* multi-layer substrate **112**. In the second position, which is illustrated by MEMS device **100-2**, a portion of the MEMS device, predominantly element portion **110**, is disposed above upper surface **120** of multi-layer substrate **112**.

For clarity and for the purposes of exposition, when MEMS device **100** is in the first position, it (and/or element portion **110**) is referred to herein as being "**within**" or "**in**" multi-layer substrate **112**. When MEMS device **100** is in the second position, it (and/or element portion **110**) is referred to herein as being "**outside**" of multi-layer substrate **112**.

In the illustrative embodiments, the movement of element portion **110** between the first and second positions results from the combined action of torsional members **104**, actuating plate **108** and electrode **326** (*see* FIG. 3) that is disposed on electrode layer **124** that abuts bottom multi-layer substrate layer **114**.

In particular, in the absence of an actuating force, element portion **110** remains in the first position within multi-layer substrate **112**. This state is illustrated, via a cross-sectional view, in FIG. 3. When a potential difference is created across electrode **326** of electrode layer **124** and actuating plate **108**, an electrostatic force is generated therebetween. This force draws actuating plate **108** toward electrode **326**. As this occurs, and in response thereto, element portion **110** rises above upper surface **120** of multi-layer substrate **112**, as is depicted in FIG. 4.

In the embodiment depicted in FIGS. 1-4, torsional members **104** twist to allow the MEMS device **100** to rotate relative to multi-layer substrate **112** allowing actuating plate **108** to move toward electrode **326**. In other embodiments, other support arrangements (*i.e.*, other than torsional members) for movably coupling MEMS device **100** to multi-layer substrate **112** may suitably be used.

*Illustrative Fabrication Method*

As indicated above, the present MEMS devices are advantageously formed from substrate **112**, itself. To this end, substrate **112** comprises several layers, such as layers **114**, **116** and **118** that are depicted in FIGS. 1-4.

The present MEMS devices can of course be fabricated in a wide variety of configurations to satisfy the requirements of a particular application. It will be appreciated that, as a function of MEMS device configuration, the thickness of the layers of the multi-layer substrate, and even the arrangement of the layers, might vary from the guidelines provided below for the illustrative configuration. It is within the capabilities of those skilled in the art to modify the nominal thicknesses and the arrangement of the various layers of the multi-layer substrate as is necessary or desirable to satisfy the requirements of any particular application.

For the MEMS devices described herein, suitable multi-layer substrates advantageously comprise at least three layers, including a first layer (*e.g.*, top, relatively thin layer **118**), a second layer (*e.g.*, bottom, relatively thick layer **114**), and an intermediate, relatively thin layer (*e.g*, layer **116**) that is sandwiched between the first and second layers. The first (top) layer and intermediate layer each have a thickness that is in the range of about 1 to 2 microns. The second layer has a thickness in the range of about 300 to 700 microns.

In accordance with the present teachings, the second layer, which in the illustrative embodiments is the bottom, relatively thick layer, is used to form element portion **110**. The "height" (from the perspective of FIGS. 3 and 4) of a major surface of element portion **110** (*i.e.*, the surface that is depicted in the cross sectional views of FIGS. 3 and 4) is advantageously defined by the thickness of the bottom layer (*e.g.*, layer **114**) of the multi-layer substrate. For simplicity of description, this major surface is referred to herein as the "**working surface**" of element portion **110**.

The relatively first layer, which in the illustrative embodiments is the top, relatively thin layer, is used to form support portion **102** of MEMS device **100**, including actuating plate **108**, torsional members **104** and beam **106**. The intermediate layer serves as an etch/milling stop between the two layers. While it is possible to fabricate a MEMS device without the use of an etch-stop (*i.e.*, the intermediate layer), it is substantially more difficult to control the extent of the etching/milling step without it.

The top and bottom layers of multi-layer substrate **112** comprise, without limitation, silicon or polysilicon. Since the intermediate layer functions as a "stop-etch" layer, it must

therefore comprise a material that resists being etched by processes that will readily etch the top and bottom layers. For instance, if silicon or polysilicon is used for the top and bottom layers, silicon oxide is advantageously used for the intermediate layer.

In one particularly advantageous embodiment, multi-layer substrate **112** comprises a silicon-on-insulator ("SOI") wafer. Such wafers typically comprise a bottom bulk or "thick" silicon layer (about 500 to 700 microns in thickness as a function of wafer diameter), an oxide layer (about 0.2 to 3 microns in thickness) disposed thereon, and a "thin" silicon layer (about 0.1 to 10 microns) that is disposed on top of the oxide layer. The arrangement and thickness of such layers are consistent with the nominal ranges for layer thickness that have been previously provided. SOI wafers are commercially available from SOITEC USA, Inc. of Peabody, Massachusetts and others.

When fabricating MEMS devices **100** using a SOI wafer, torsional members **104**, beam **106** and actuating plate **108** are advantageously formed from the thin silicon layer and element portion **110** is advantageously formed from the thick silicon layer. In some embodiments, a SOI wafer (in particular, the thick silicon layer) having a <110> crystal orientation is used. In such embodiments, the wafer can be oriented so that the working surface of element portion **110** is an atomically flat <111> surface. Since each element portion **110** comprises a section of the same single crystal silicon, the working surface of the element portion of each MEMS device **100** in an array of such devices are parallel to one another to a high degree of accuracy.

The ability to precisely align the element portions and provide exceedingly smooth, flat surfaces is particularly advantageous for optical applications, a few of which are described later in this *Specification*.

A method for making a MEMS device is now described in conjunction with FIGS. 5 - 8. The illustrative fabrication method utilizes standard patterning and etching techniques (*e.g.*, photolithographic processing, *etc.*) Since these techniques are commonplace in the art, they will be referenced without explanation.

In accordance with operation **502** of method **500** depicted in FIG. 5, support portion **102** is defined in a multi-layer substrate **112**. In one embodiment, operation **502** is carried out via steps **604** and **606** depicted in FIG. 6. In particular, support portion **102** is defined by appropriately patterning and etching the top layer (*i.e.*, layer **118**) of the multi-layer substrate (step **604**), and by appropriately patterning and etching the bottom layer (*i.e.*, layer **114**) of the multi-layer substrate (step **606**).

FIG. 7 depicts a view of top layer **118** after etching and patterning in accordance with step **604**. After patterning, top layer **118** is etched (*e.g.*, via reactive ion etching, *etc.*) such that trench **222**, which substantially encompasses or surrounds support portion **102**, extends "down" to intermediate layer **116**. Trench **222** defines the shape of actuating plate **108**, torsional members **104** and beam **106**.

FIG. 8 depicts a view of bottom layer **114** after etching and patterning in accordance with step **606**. After patterning, bottom layer **114** is etched (*e.g.*, via DRIE, laser milling, *etc.*) "up" to intermediate layer **116**. A thin "slice" of layer **114** is masked such that it remains after etching. That slice becomes, in the illustrative embodiment, element portion **110**. And the thickness of layer **114** defines the "height" (from the perspective of FIGS. 3 and 4) of the working surface of element portion **110**.

Bottom layer **114** advantageously comprises silicon having a <110> crystal orientation, which can be oriented so that the working surface (*i.e.*, the vertical face) of element portion **110** comprises <111> facets. After etching, element portion **110** is washed (*e.g.*, KOH, *etc.*) to clean the <111> facets.

After defining the MEMS device **100** as per operation **502**, it is released, as per operation **508**. In the illustrative embodiment of the present method, release is effected by removing the portions of intermediate layer **116** that are exposed due to the previous etching steps. Bottom layer **114** of multi-layer substrate **112** is then bonded, in operation **510**, to a second substrate (*e.g.*, substrate **124** of FIGS. 1, 3, 4) that is patterned with electrodes. Top layer **118** and bottom layer **114** of multi-layer substrate **112**, and the portions of MEMS device **100** formed from those layers, are electrically grounded.

*Physical Design Example*

A MEMS device **100** is to be fabricated from a SOI wafer comprising a thin silicon layer having a thickness $t$ and a thick silicon layer having a thickness $t_0$. With reference to FIG. 9, other length parameters include length $L$ of actuating plate **108**, the length $L_t$ of torsional members **104**, the width $w$ of torsional members **104**, the distance $d$ between the center of torsional members **104** and the leading edge of actuating plate **108**, the distance $D_1$ between the center of torsional members **104** and the trailing edge of actuating plate **108** and the distance $D_2$ between the center of torsional members **104** and the end of beam **106** or element portion **110**.

Assuming further that $d/D_1 < 0.2$, $L = 2D_1$ and that $w = t$, then the voltage $V_c$ and the corresponding rotation angle $\theta_c$ at which snap down (*i.e.*, electrostatic instability) occurs are given by:

[1] $V_c \approx 2.6 \times 10^4 [(tt_0^{1.5})/(L_t^{0.5} D_1^2)]$

[2] $\theta_c \approx 25.2 t_0 / D_1$

where: length/distance is measured in microns and angle is measured in degrees.

Given:

thin silicon layer thickness $t =$ 2 microns;
thick silicon layer thickness $t_0 =$ 200 microns; and
the distance $D_1$ = 400 microns, then:

[3] $V_c = 1810 / L_t^{0.5}$ ; and

[4] $\theta_c = 12.6°$.

So, if $L_t =$ 200 microns, then:

[5] $V_c =$ 128 volts.

Assuming that the maximum working voltage $V_{mw}$ would be ninety percent of $V_c$, then:

[6] $V_{mw} =$ 115 volts.

It is seen from FIG. 10, which is a plot of $\theta / \theta_c$ vs. $V / V_c$, that when $V / V_c = 0.9$, then:

[7] $\theta / \theta_c \approx$ 0.55.

Therefore, for a maximum working voltage of $0.9 V_c$, the maximum working rotation angle $\theta_{mw}$ is:

[8] $\theta_c = 7°$.

If the distance $D_2$ = 800 microns, then the outside edge of element portion **110** is raised a distance of 800 *tan* 7° or 100 microns above surface **120** of multi-layer substrate **112**.

*Illustrative Optical Applications*

As previously indicated, the present MEMS device is well suited for optical applications, among other uses. Two of such optical applications are described below.

1. Chopper Switch

In a very simple optical application, an on/off switch is created by positioning a movable plate such that it can be moved into or removed from the path of an optical signal that is traveling between two waveguides. *See, e.g.*, U.S. Pat. No. 5,923,798. Such switches are often referred to as "chopper" switches. An improved version of a chopper switch in accordance with the present invention is depicted in FIGS. 11 – 12.

FIG. 11 depicts a top view of improved chopper switch **700**. In accordance with the present teachings, chopper switch **700** includes two optical waveguides (*e.g.*, fibers, *etc.*) **728** and **730** that are disposed end-to-end and separated by gap **736**. Chopper switch **700** also includes MEMS device **100** that is arranged so that the portion of trench **222** that houses element portion **110** is disposed beneath gap **736**. The working surface of element portion **110** is advantageously highly reflective.

FIG. 11 depicts the cross state of switch **700** wherein optical signal **734** travels from waveguide **728**, across gap **736**, to waveguide **730**. In the cross state, element portion **110** is within multi-layer substrate **112** and, therefore, does not impinge upon the path of optical signal **734**.

FIG. 12 depicts, via a side cross-sectional view through axis **1-1** of FIG. 11, the bar state of switch **700**, wherein optical signal **734** does not cross (*i.e.*, is "barred" from crossing) switch **700**. In the bar state, the working surface of element portion **110** intercepts optical signal **734**, thereby preventing it from entering waveguide **730**. Switch **700** is placed in the bar state by actuating MEMS device **100**, such as by applying a potential difference across electrode **326** and actuating plate **108**, so that element portion **110** moves out of multi-layer substrate **112** and between waveguides **728** and **730**.

The embodiment of MEMS device **100** depicted in FIGS. 11 and 12 (hereinafter "configuration B") for use in chopper switch **700** has a different configuration than MEMS device **100** illustrated in FIGS. 2-4 and 6-7 (hereinafter "configuration A"). In particular, in configuration A, beam **106** extends over element portion **110** (*see, e.g.*, FIG. 4), while in configuration B, beam **106** does not extend over element portion **110** (*see, e.g.*, FIG. 12).

The reason for this difference is that for a chopper switch it is usually advantageous to keep the size of gap **736** as small as possible. In this context, observe that beam **106** is wider than element portion **110**. Consequently a relatively wider-sized gap would be required to accommodate the relatively greater width of beam **106** for a MEMS device having configuration A than for a MEMS device having configuration B.

A second difference between configuration A and configuration B of MEMS device **100** is the presence of, in configuration B, stabilization region **838**. Stabilization region **838**, which flares outwardly with increasing distance from element portion **110**, provides additional rigidity to MEMS device **100**. There is nothing unique to the chopper switch application that demands the presence of stabilization region **838**; this feature is suitably incorporated into the present MEMS devices for use in a wide variety of applications.

Optical Cross Connect

FIG. 13 depicts optical cross connect **900** in accordance with the present invention. Optical cross connect **900** comprises a *n* x *n* array of MEMS devices **100**. In the embodiment depicted in FIG. 13, $n = 3$, such that there are three columns of MEMS devices **100** (labeled columns 1, 2 and 3) and three rows of MEMS devices **100** (labeled A, B, C). It will be understood that in other embodiments of cross connect **900**, *n* is less than 3, and in still further embodiments of cross connect **900**, *n* is greater than 3.

An optical signal **948** is delivered to cross connect **900** by a first 1 x *n* array of input waveguides **940-*i*, *i*= 1, *n***. A second 1 x *n* array of output waveguides **946-*i*, *i*= 1, *n***, receives optical signal **948** from cross connect **900**. In the embodiment depicted in FIG. 13, $n = 3$ such that there are three input waveguides **940-1**, **940-2** and **940-3**, and three output waveguides **946-1**, **946-2** and **946-3**.

In the illustrative embodiment, a first 1 x *n* array of lenses **942-*i*, *i*= 1, *n***, is disposed between input waveguides **940-*i*** and columns **1**, **2** and **3** of MEMS devices **100**. More particularly, one lens (*e.g.*, **942-1**) is disposed between each input waveguide (*i.e.*, waveguide **940-2**) and the optically aligned column (*i.e.*, column **2**) of MEMS devices **100**. Similarly, a second 1 x *n* array of lenses **944-*i*, *i*= 1, *n***, is disposed between rows **A**, **B** and **C** of MEMS devices **100** and output waveguides **946-*i***. Lenses **942-*i*** collimate the optical signal as it leaves the input waveguides **940-*i***, and lenses **944-*i*** focus the optical signal into output waveguides **946-*i***.

By selectively actuating an appropriate MEMS device **100**, optical cross connect **900** is operable to route an optical signal, which can be delivered via any one of the *n* input waveguides **940-*i***, to any one of the *n* output waveguides **946-*i***. For example, in FIG. 13, optical signal **948**, which is delivered by input waveguide **940-2**, is routed to output waveguide **946-2** by actuating MEMS device (**B, 2**). If the signal were instead to be routed to output waveguide **946-3**, then MEMS device (**C**, 2) must be actuated.

The MEMS devices **100** of cross connect **900** are actuated in the manner previously described by electrodes (not depicted in FIG. 13) that underlie the MEMS devices on an electrode wafer. Typically, each electrode will be individually connected, via a wire trace, to electrical contact pads that are disposed at the edge of electrode wafer. Such contact pads will be in electrical contact with a controlled voltage source that is operable to selectively apply voltage to an appropriate pad to actuate a desired electrode.

In cross connect **900**, element portion **110** is oriented at 45 degrees with respect to sides **950** and **952**. This is a consequence of the orientation (orthogonal) of the input and output waveguides relative to each other and of the orientation (orthogonal) of the waveguides with respect to sides **950** and **952**.

The individual MEMS devices **100** of cross connect **900** have a structural configuration that is different than configurations A or B previously depicted and described. In particular, while MEMS devices **100** that are depicted in FIG. 13 possess the same elements as in the previous embodiments (*i.e.*, torsional members **104**, beam **106**, actuating plate **108**, element portion **110** and stabilization region **838**), the shape of the MEMS device is different. More particularly, actuating plate **108** of the MEMS devices depicted in cross connect **900** has a shape that (1) facilitates close packing of MEMS devices and (2) prevents shorting if electrostatic snap-down occurs. In further detail, notch **954** in actuating plate **108** allows for closer packing, and points **956** contact electrode layer **124** rather than electrode **326** if snap-down occurs (*see* FIG. 4).

It is to be understood that the above-described embodiments are merely illustrative of the invention and that many variations may be devised by those skilled in the art without departing from the scope of the invention and from the principles disclosed herein. It is therefore intended that such variations be included within the scope of the following claims and their equivalents.